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Geopolymer concrete cured under ambient conditions using a single alkali activator

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ABSTRACT

In order to meet sustainability criteria and reduce carbon emissions associated with the production of cement and its related composites, it is necessary to completely replace Ordinary Portland Cement (OPC) with a new binding substance. This study focuses on a novel method of manufacturing geopolymer concrete by utilizing a single activator instead of the traditional two activators. An analysis was conducted on the mechanical properties and microstructure of geopolymer concrete made from several source materials, including Fly ash (FA), granulated blast furnace slag (GGBS), and nano silica (NS). The findings indicated that the mechanical characteristics of GPC, generated by combining 80% GGBS and 20% FA, using a single source alkali activation method under ambient curing conditions for 28 days, had superior performance compared to other mixtures. Additionally, there was a decrease in carbon emissions.

Keywords: Carbon emission; Geo-polymer concrete; Single activator; SEM analysis.

1. INTRODUCTION

The production and usage of concrete have increased dramatically due to the growing global population and the demand for more infrastructure. Globally, cement industries are contributing around 8% of the world's total carbon di oxide emission [1, 2]. The conventional ordinary Portland cement (OPC) is the main binding material of concrete, and the production of 1 m^3 concrete emits around 1000 kg of CO_2 according to the carbon foot print of cement industries data [3, 4]. Along with greenhouse gases, a significant number of fine dust particles are also released into the environment during the manufacture of OPC [5]. Specialists are investigating substitutes for OPC (Ordinary Portland Cement) as one of the major binding agent in the production of conventional concrete in order to fulfil sustainability criteria and develop more environmentally friendly construction materials. By activating silica and crystalline alumina in materials with a high alkalinity, the geopolymer binder can be produced. Geopolymer binder has been proposed as a good viable substitute for cement in concrete, which would result in decreased carbon emissions and energy usage with better performance [1, 6].

In the process of making geopolymer concrete, industrial by products such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) are utilised. This type of concrete is regarded as ecologically sustainable. GGBS and fly ash are both secondary ingredients derived from other processes, and their incorporation in concrete production enhances its overall sustainability. Utilising geopolymer concrete in construction obviates the necessity for cement in the concrete mixture, hence leading to a drop in carbon dioxide emissions and a reduction in energy consumption throughout the concrete making process GGBS, or Ground Granulated Blast Furnace Slag, is frequently used as a waste material in the production of geopolymer concrete. The use of Ground Granulated Blast Furnace Slag (GGBS) into fly ash-based geopolymer concrete, even at a concentration of 4%, enhances its strength and decreases energy consumption [7]. Depends on the type of activator and its concentration is one of the major permeator for strength development [7, 8]. Researchers found a way to make stronger geopolymer concrete that sets faster and performs better at normal temperatures. The key is using starting materials with a lot of calcium oxide (CaO) [8].

Geopolymer concrete differs from normal concrete in the way it attains strength. It does not depend on the development of calcium silicate hydrate (C-S-H) gel for the process of solidifying and becoming hard. On the other hand, the alumino-silicate polycondensation is the source of its extraordinary strength [9]. The presence of cement is not required for the use of geopolymer binders. In order to manufacture such a binder,

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it Geopolymer binders can be used without the need for cement. To produce this binder, two essential raw materials are required: a reactive solid mineral, which is an alumino-silicate substance like calcinated clay or fly ash (providing Si and Al), and an activating solution that is alkaline, such as a silicate solution or a hydroxide solution. Typically, a little higher temperature is necessary to initiate the geopolymerization process [2, 10]. Due to the difficulties in heating them on site, the use of heat-cured geopolymer concretes is limited to precast members and is not economically viable.

A mixed alkali activator made of sodium hydroxide and sodium silicate was used in a study by RAFEET *et al.* [11] to examine the effects of adding GGBS to fly ash-based geopolymer mortar that had been cured under ambient conditions. When GGBS was added, even in little amounts, the researchers discovered that heat curing was no longer necessary for a new fly ash-based geopolymer that had been cured in an oven. Multiple previous studies have been undertaken [11–14] have reported that the level of improvement in the mechanical and microstructural characteristics of the geopolymer mix that is achieved is directly proportional to the amount of GGBS that is added to the mixture. In their explanation, they referred to this phenomenon as the primary outcome of the geopolymerization process, which was the increasing buildup of C-A-S-H reaction gel. According to research by ODERJI *et al.* [14], small cracks in a single-component fly ash geopolymer concrete cured at ambient temperature resulted from adding more than 15% ground granulated blast furnace slag (GGBS).

Furthermore, geopolymer has been formed using coal bottom ash. At a temperature of 800 °C, the ash undergoes a transformation, becoming highly reactive without requiring additional energy for activation [15–18]. It was demonstrated that there is a direct correlation between the particle size of fly ash and its flow and strength of the geopolymer binder mortars [19]. Surface area and reactivity potential of fly ash are increased by grinding it. The reactivity of finer ash components is increased, and bottom ash particles have less holes [19]. MAHARAJAN *et al.*, [20] established medium-strength geopolymer concrete that cures in the ambient environment. As binders, they used equal parts of bottom and fly ash. Though its compressive strength was same to that of OPC concrete, its tensile and flexural strengths were lower. Ghosh and colleagues used fine aggregate made of bottom ash in geopolymer concrete [21]. However, the reaction of geopolymerization was not impacted, as it is mostly controlled by fly ash and GGBS. XIE and OZBAKKALOGLU [22] illustrated this phenomenon by the utilisation of SEM micrographs depicting cured fly ash and bottom ash concrete samples at room temperature. As the ratio of fly ash to bottom ash increased, microscope photos showed that the geopolymer concrete samples became denser and more uniform. The study revealed that the fly ash particles had superior compressive strength compared to the bottom ash particles, indicating a higher level of geopolymerization.

The literature on ambient-cured single alkaline activator geopolymer concrete is limited, with most investigations focusing on heat-cured concrete with double alkaline activator. Ambient-cured concrete manufacturing has problems, such as blending a few alkali activators or raising their concentration to obtain acceptable strength. While there is a lot of study on ambient cured geopolymer concrete, single alkali activated concretes or pastes are not well studied. This study attempts to develop sustainable ambient-cured geopolymer concrete utilising a medium-concentration alkali activator. The investigation aims to find the best geopolymer concrete mix with the highest overall performance, using various combinations of cementitious elements to replace cement altogether.

2. MATERIALS AND METHOD

2.1. Different concrete mixtures

For this experimental study, totally seven numbers of concrete mixtures were prepared with different combinations of binding materials. The concrete mix, designated as (C), was made with regular Portland cement. The remaining combinations were made with varying amounts of fly ash, GGBS, and nano silica as binding materials. On other hand the amount of course aggregate, fine aggregate and water were fixed for all the mixtures and eliminating the effects of their variations. The same amount of activated solution was used for all the geopolymer concrete mixtures. Table 1 shows the % combinations of all the concrete mixtures. In order to enhance the workability of the concrete Glenium 53 super plasticiser at 1% by weight of binder was used. The Nano silica content of 5% was fixed based on the literature [23].

2.2. Characterization of different materials

OPC, fly ash (FA), GGBS, nano silica (NS), and a 12M NaOH solution were utilised as the activator solution for the geopolymerization process in this experimental study. Table 2 displays the specific characteristics of the coarse and fine aggregates. The crushed granite particles were used as the coarse aggregates, which was collected from Annai blue metals, Thorticode, India. To ensure quality, the project used conventional river sand

Table 1: Combinations of the concrete mixtures.

SL. NO	DIFFERENT MIX ID	OPC	FLY ASH (FA)%	GGBS%	NANO SILICA (NS)%
1	C	100	–	–	–
2	100 FA	–	100	–	–
3	100 G	–	–	100	–
4	80F20G	–	80	20	–
5	80F17G5NS	–	80	15	5
6	95F5NS	–	–	95	5
7	80G17F5NS	–	15	80	5

Table 2: Physical properties of different aggregates.

SL. NO	CHARACTERISTICS OF MATERIALS	COARSE AGGREGATE (CA)	FINE AGGREGATE (FA)
1	Specific gravity (kg/m^3)	2.61	2.5
2	Bulk density loose (kg/lt)	1563 kg/m^3	1436 kg/m^3
3	Fineness modulus	3.7	2.77
4	Water absorption (per unit by weight)	1.24%	Nil
5	Abrasion mass loss	18%	–
6	Silt content	–	3.14

Table 3: Different chemical composition of binders.

SL. NO	NAME OF THE MINERALS	FLY ASH (%)	GGBS (%)	NANO SILICA (%)	OPC
1	SiO_2	58.17	34.16	99.64	21.42
2	Al_2O_3	32.07	20.13	0.042	4.16
3	Fe_2O_3	3.16	0.92	0.002	3.86
4	CaO	2.27	34.62		63.26
5	SO_3	0.18	0.2		3.62
6	MgO	0.46	6.42		1.94
7	Na_2O	0.62	–	0.001	–
8	K_2O	0.66	–	0.004	0.42
9	TiO_2	–	–	0.002	–
10	LoI	2.41	3.55	0.309	1.32

as the fine aggregate, obtained from authorized government quarries located in Piliyar Natham, Thootukudi District, India. Fly ash, ground granulated blast furnace slag (GGBS), and nano-silica's chemical makeup are shown in Table 3. The sodium hydroxide pellets were obtained from a local supplier and had a purity level of 99%. To prepare the 12M NaOH solution, 480 gm of NaOH pellets were dissolved in 1 L of tap water, and it allowed to cool down in room temperature for 24 hours in normal atmospheric pressure. The liquid to binder ratio of all the geopolymer concrete and control concrete mixtures were kept constant as 0.4.

2.3. Preparation of concrete

The conventional concrete preparation method was followed for preparation of GPC. To achieve a uniform blend, coarse and fine particles were vigorously stirred in a pan for two minutes. Next, the appropriate amount of reactive materials was combined for a further two minutes. Then, the activated solution was added and well mixed until a uniform mixture was achieved. When using GGBS, the amount of mixing lime is somewhat reduced in order to prevent rapid solidification, as opposed to using fly ash [5]. Ultimately, super plasticizers were used to augment the malleability and facilitate the process of blending. Geopolymer concrete typically exhibits a ball-like consistency throughout the mixing process, owing to its rigid and inflexible nature. Previous research have revealed that it requires around 0.3 times the amount of water content compared to free water [6, 9].

2.4. Tests on fresh concrete and concrete specimen preparation

The workability of the concrete mixes was assessed by conducting a slump test, as per the guidelines outlined in IS: 1199-1959, after the concrete was well mixed [24], the air content on fresh concrete and density was also examined by using the same code provision. The compressive strength test utilised cubical specimens measuring 150 mm × 150 mm × 150 mm, while the split tensile strength test employed specimens measuring 150 mm × 300 mm, in accordance with the requirements outlined in IS 516-1959 [25], IS 5816-1999 [26] respectively. The, mixed concrete were placed in a steel mould filled with three different layers and compacted by using manually mild steel tamping rod and compacted using table vibrator for releasing the air bubbles present in the concrete. The specimens were encased in a polyethylene sheet to prevent evaporation and stored at room temperature for a duration of seven days. Following their removal from the concrete mould, the specimens were kept for ambient curing at room temperature until they were tested. Concurrently, three samples were extracted from each mixture and subjected to heat curing by placing them in an oven at a temperature of 60 °C for a duration of 24 hours. The samples that were cured in the surrounding environment were tested on the 7th and 28th days after they were made, while the samples that were cured with heat were evaluated on the 28th day. To conduct morphological analysis, representative samples were obtained by cutting 10 mm diameter and 5 mm thickness sections from the middle of the sample using a diamond cutter.

2.5. Test on mechanical property and characterization

The concrete samples hardened properties like compressive and split tensile strength of both ambient and hot cured samples were examined by the guidelines of IS 516-1959 [25], IS 5816-1999 [26] respectively. The ambient cured samples were examined on 7th and 28th days, while hot cured samples were tested on 28th day only. On the other hand, the SEM and XRD investigation were done for both ambient and hot cured samples on 28th day in order to understand the chemical composition and their contribution to geo-polymerization as well as morphological chances in the mineral structure.

2.6. Sustainability of geopolymer concrete mixes

The embodied carbon dioxide of each mix was calculated in the study by combining the components used to make the geopolymer concretes. The carbon emissions associated with the production of geopolymer concrete mixes were calculated using the factors recommended by FLOWER and SANJAYAN [27]. The composition of each mix and the quantities of elements used determined the outcome. Obtaining data on a product's atmospheric impact from the point of extraction to the end of manufacturing is essential when doing this kind of assessment [28, 29]. The fact that fly ash and GGBS are byproducts of steel and thermal power plants and have no carbon emission value should not be overlooked.

The different parameters for comparing CO_2 emissions are shown in Table 4. These emissions are measured in kilogrammes per kilogramme of concrete component that was utilized in this experimental study. When calculating the CO_2, the quantity of each component that was utilised in the production of a concrete mixture was multiplied by the carbon factor that corresponded to that component. The embodied carbon footprint of the complete mixture was calculated by summing the carbon emissions associated with each individual component.

For the purpose of this study, an economic feasibility analysis was carried out by estimating the amount of money that would be necessary to produce one cubic meter of each mix in the Indian market. Table 5 shows the price of all the concrete making substance individually. As, water is freely available all around India, the cost of water was not taken into account.

Table 4: Co_2 emission factor.

NAME OF THE INGREDIENT	EMISSION FACTOR (CO_2) (kg CO_2-e/kg)	LITERATURE
Fly Ash	0	–
GGBS	0	–
Cement	0.8200	[27]
Fine aggregate	0.0139	[27]
Coarse aggregate	0.0050	[28]
Nano silica	0.135	[28]
NaOH	1.915	[30]
Concrete mixing and placing	0.0033	[27]

Table 5: Cost of GPC making substance.

NAME OF THE MATERIAL	PRICE/m^3 (INR)	PRICE/kg (INR)
OPC		5.40
Coarse aggregate	2600	1.66
Fine aggregate	4500	3.14
Fly ash		2.00
GGBS		2.15
NaOH		36.65
Nano silica		2800.00
Super plasticizer		106.00

Table 6: Fresh properties of concrete.

MIX ID	SLUMP (mm)	AIR CONTENT (%)	DENSITY (kg/m^3)
C	80	2.14	2486
100 FA	21	3.45	2146
100 G	5	3.87	2265
80F20G	16	3.14	2183
80F15G5NS	0	3.37	2168
95F5NS	0	3.23	2154
80G15F5NS	0	3.48	2219

3. RESULT AND DISCUSSION

3.1. Fresh properties of concrete

Table 6 displays the outcomes of the inherent characteristics of concrete. Significantly reduced workability was reported in comparison to the control concrete mixture. In order to maintain good strength, the addition of free water and superplasticizer was maintained low, while the amount of alkaline solution on its effect on workability of all the geopolymer concrete mixtures were fixed at 142 kg/m^3. On other hand the addition of GGBS also reduced the workability. Previous studies also reported that the geopolymer concrete made by GGBS affect the slump value [3–5]. However, it is to be importantly noted that the inclusion of Nano silica with fly ash and GGBS in geopolymer concrete leads to zero slump value. All the geopolymer concrete mixtures samples exhibited slightly viscous with sticky nature, which might be because of the sticky nature of NaOH alkaline solution. The same sticky and viscous effect was found in previous studies when using NaOH [31]. However, the 80F20G mix shows 16 mm slump value, which could be because of the addition of very small amount of GGBS (20%) addition as well as the effect of superplasticizer without nano silica.

From Table 6, the amount of air content present in the geopolymer concrete was observed to be higher than the control concrete mix. It is noted that 100% GGBS shows more void content rather than other mixes, and typically the inclusion of GGBS enhanced the amount of air content, meanwhile the inclusion of NS reduced the air content present in the concrete. However, all the geopolymer concrete mixes were under the acceptable limits of IS: 1199–1959. The reduction of air content present in the GPC may be possible in two ways, with both having other demerits, one is to increases the amount of alkaline solution, which induces brittleness to the concrete or increasing the addition of fine particles, which affects the workability.

The unit weight of GPC exhibits lesser value compared to conventional concrete. The density reduction in GPC concrete may be because of its high void content rather than the conventional concrete. Workability is also one of the main factors to enhance the void content. However, all the GPC mixers are within the proposed range of geopolymer concrete according to previous literatures [10]. Hence, the proposed geopolymer concrete mixtures are more suitable for light weight concrete applications.

3.2. Mechanical properties

An examination of the compressive and split tensile strengths was performed on the specimens of hardened concrete in order to determine their mechanical properties. The subsequent sub-sections provide the thorough descriptions of these qualities.

3.2.1. Compressive strength

The compressive strength of each of the concrete specimens was measured at 7th as well as 28th days, and the results are shown in Figure 1. It is important to note that all of the concrete specimens saw an increase in strength between the 7th and the 28th day. However, compressive strength of all the geopolymer concrete mixtures were below the compressive strength of control specimens. Among all the studied GPC samples, 80G15F5NS samples scored maximum strength of 29 MPa and 40 MPa on its 7th and 28th days respectively under ambient curing condition. It is also noticed from Figure 1, that the addition GGBS enhances the strength rather than fly ash. For example, 80F20G samples scored the maximum compressive strength of 24 MPa, meanwhile 100FA specimens exhibits only 5 MPa, which was around five times lower strength when compared to 80F20G samples. The strength enhancement while adding GGBS in GPC was because the amount of calcium present in the GGBS is high when compared to Fly ash, which promoted the calcium silicate gel formation rather than the conventional GPC binder of alumino-silicate gel. Previous studies also recorded the similar strength enhancement while partially adding GGBS in geopolymer concrete [8].

It is noteworthy that the addition of NS in GPC increases its strength. Among the many mixes tested, the 80F20G mix exhibited the maximum compressive strength of 21 MPa. Additionally, the 5% partial substitution of GGBS by NS (80F15G5NS) resulted in a 15% gain in compressive strength. The 80G15F5NS mix scored highest compressive strength among all the GPC mixtures, which was around 5% strength enhancements rather than 100G samples. Because silica was added, the pozzolanic reaction was accelerated and calcium aluminate silicate hydrate (C-A-S-H) was formed at a higher rate. This led to optimal packing between the inner matrix particles and an increase in strength.

The effect of heat curing was observed from Figure 1, which shows that the heat curing was effectively improved strength in samples having high amount of Fly ash. It may be because, the reaction between alkaline activator and fly ash are thermal decomposition, and it needs additional heat energy to enhance the formation of polymeric chains in alumino silicates, which is one of the main back bone structures of fly ash base geopolymer. The heat curing process accelerate the geo-polymerization process with leads to the strength enhancement rather than ambient curing technique. The same kind of effect was also recorded in previous studies with two alkaline activators [32, 33]. However, while using single alkali activator, the strength gained on heat cured 100FA samples are not in the considerable level, which could be because, sodium hydroxide alone cannot accelerate the pozzolanic reaction and the amount of produced alumino silicate gel is very low. However, adding Fly ash with GGBS produced a considerable strength. It might be because, under

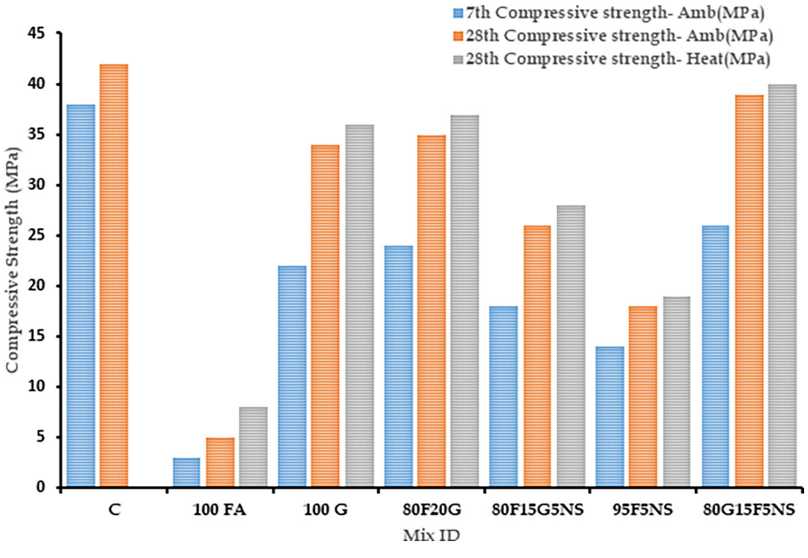

Figure 1: Compressive strength of GPC mixtures.

warm environment, the calcium oxide present in the GGBS react with silica present in the fly ash to generate C-A-H-S leading to the better particle packing inside the GPC matrix hence causing strength development Table 6 slump values of SCC mixtures.

3.2.2. Split tensile strength

The split tensile strength of the control and GPC concrete mixtures is illustrated in Figure 2. The split strength development of both concrete mixtures exhibited a similarity to the results obtained from the compressive strength test. The incorporation of three binders (Fly ash, GGBS, NS) results in the highest split tensile strength compared to the other GPC mixes. On the other hand, the combination including 100F mix samples exhibited the lowest strength compared to all other mixtures. This could be attributed to the presence of smooth-surfaced spherical particles of fly ash and the limited bond strength achieved when using a single activator. Additionally, it has been observed that the ambient cured 100G samples exhibit approximately 5% higher strength than traditional concrete. Furthermore, the high strength development occurs at an earlier stage compared to other GPC combinations. The strong link between the aggregate particles is likely due to the rough surface of GGBS particles, rather than fly ash particles. Furthermore, the use of calcium GGBS also enhances the development of alumino silicate polymeric chains in later stages. The bond strength in geopolymer concrete is enhanced by the deposition of alkaline activator on the surface of the aggregate. GPC (Ground Granulated Blast Furnace Slag) exhibited comparable surface buildup, precipitation of alumino silicate gel, and improvements in split tensile strength and flexural strength, as reported in previous studies [34, 35].

3.2.3. SEM analysis

The SEM image of both ambient and heat cured samples of 100F, 100G and 80G15F5NS were presented in 3-a, 3-b-3-c, 3-d, 3-f and 3-d respectively. The ambient cured sample with fully fly ash (Figure 3a), showed plenty of spherical shaped un hydrated fly ash particles without crack while, the heat cured samples (3-b) exhibited some crack with un hydrated fly ash particles. It is evident that single alkaline activator could be able to fulfil the need of geo-polymerization under temperature also. However, SEM image of the F100 samples showed loose packing with high number of pores with larger pore size. The 100G samples are exhibit well hydrated with good packing with some small pores, while the heat cured samples exhibited cracks with nano level crack width. It is evidenced that the heat curing initiates the crack formation in GPC mixtures rather than ambient cured samples. Previous studies also recoded the same findings [36, 37].

GPC samples with NS dosage are showed in 3-d and f. The results show that the ambient cured sample (3-d) have some small pores compared to 100G samples along with some un hydrated nano silica particles on other hand, the heat cured sample (3-f) also exhibited small pores with very minor cracks, with no evident un hydrated nano silica particles. So, the heat treatment enhanced the hydration of silica materials, while it promoting crack formation in the inner matrix. Overall, the 100G and 80G15F5NS samples are found to be denser than 100F samples with well hydration and good packing between the particles.

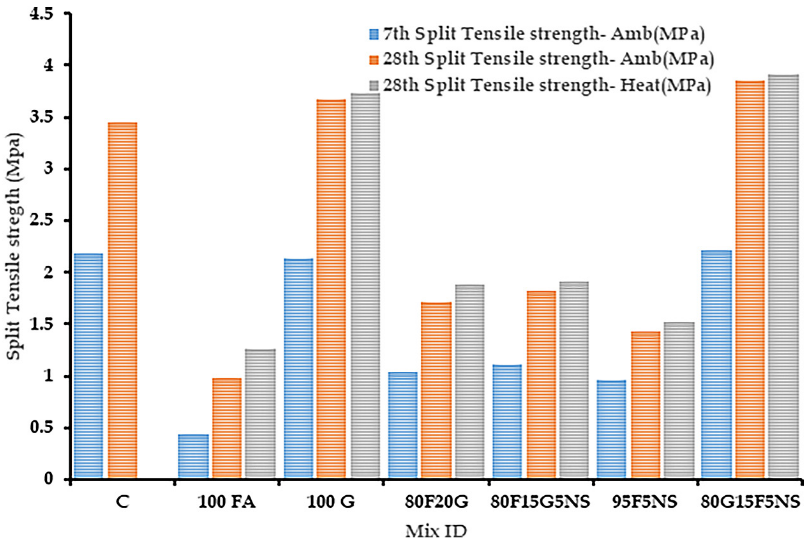

Figure 2: Split tensile strength of GPC mixtures.

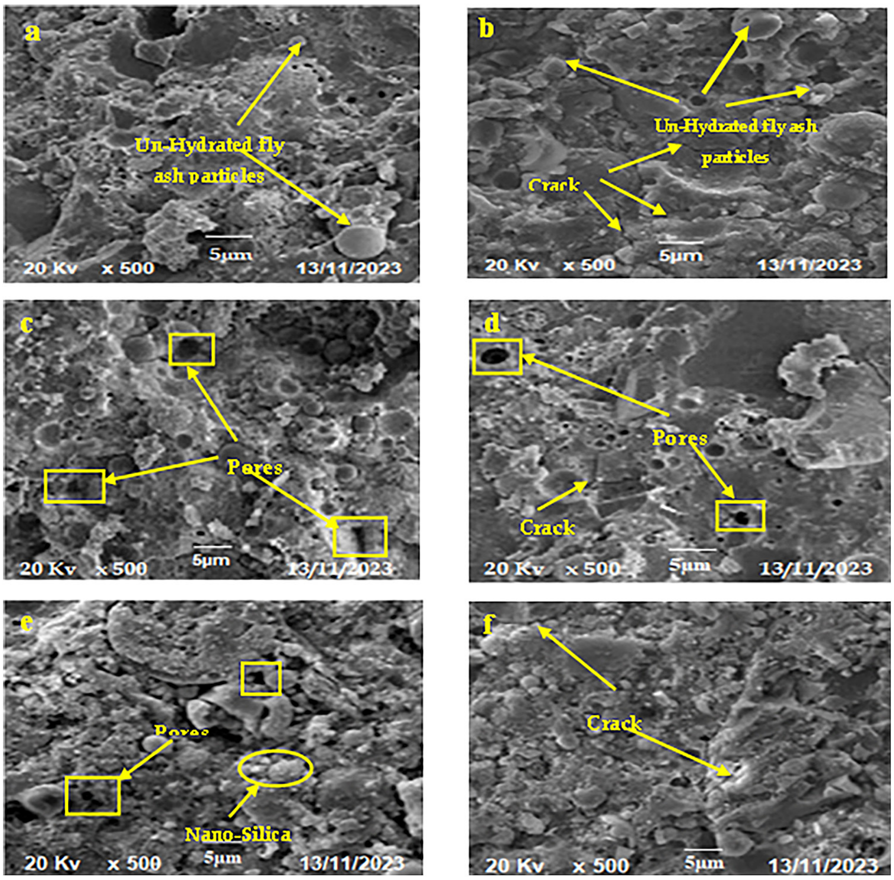

Figure 3: SEM image GPC mixtures. a) 100FA- 7th day, b) 100FA- 28th day, c) 100G- 7th day, d) 100G- 28th day, e) 80G15F5NS- 7th day, f) 80G15F5NS- 28th day.

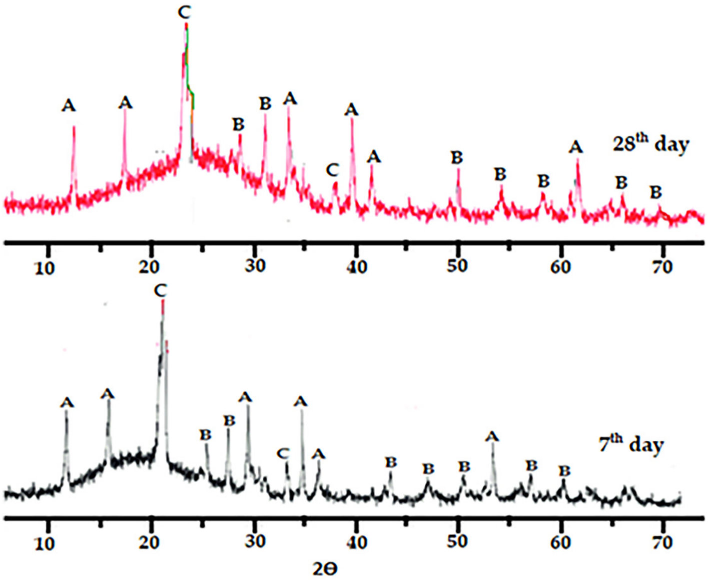

Figure 4: XRD humps of 100FA samples.

3.2.4. XRD analysis

The XRD humps of both ambient and heat cured samples of 100F, 100G and 80G15F5NS were presented in Figures 4, 5 and 6. The chemical composition of both 100F (Figure 4) samples showed almost un-polymerized fly ash particles with small amount of Si/Ai ratio. The low calcium fly ash hydrated products like alumino silicate and calcium silicate gel in both mixtures were not in the considerable level. This is the major reason behind the strength reduction.

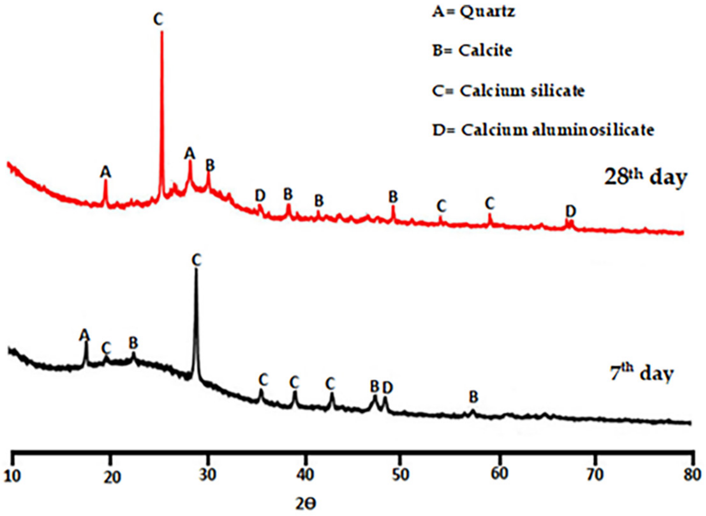

Figure 5: XRD humps of 100G samples.

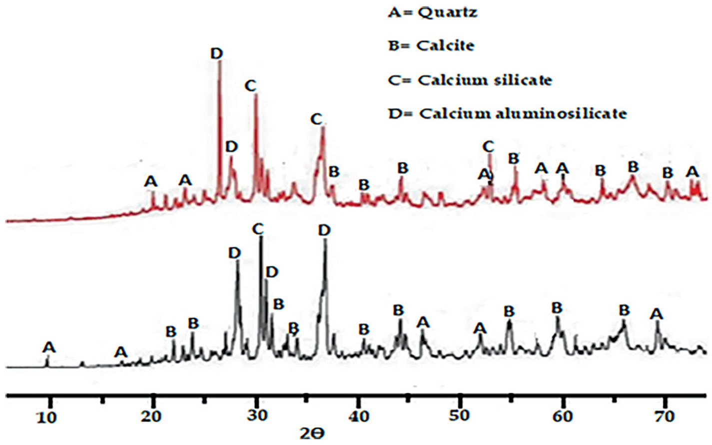

Figure 6: XRD humps of 80G15F5NS samples.

On other hand, 100G specimens (Figure 5) chemical composition of ambient cured and heat cured samples Si/Ai ratio were around 8.6% and 9.7% respectively. Moreover, both samples have a very high Ca/Si ratio compared to 100F samples. This is the important chemical composition to enhance the geo-polymerization process while using singe activator and produced predominate amount of C-A-H-S and C-H-S leading to strength enhancement.

It should be noted that that XRD humps of 80G15F5NS (Figure 6) samples exhibits while adding Nano-silica and fly ash that promotes the formation of calcium-alumino silicate, and high amount of alumino silicate when compared to other samples. It may be because the addition of nano-silica promotes the geo-polymerization process under ambient as well as heat curing. It is importantly noted that from the chemical composition, while using GGBS as the source material for geo-polymer concrete heat curing process did not made any considerable changes in the chemical composition, so the heat curing may lead to energy consumption as well as increase in production cost.

4. SUSTAINABILITY ANALYSIS OF CONCRETE MIXTURES

The embedded equivalent carbon-dioxide emission as well as carbon-dioxide emission reduction when compared to control concrete mixes used in this study was presented in Table 7. All the geo-polymer concrete mixtures are having almost 60% lower CO_2 emission when compared to control concrete mix, thus reducing the carbon foot print to the atmosphere. This indicates all the geopolymer concrete mixtures used in this study are more eco-friendly and enhance the sustainability. It is also noted that while using GGBS as the source material, there

Table 7: Co$_2$ emission reduction of GPC mixtures used in this study.

MIX ID	CO$_2$ EMISSION (kg-CO$_2$-eq)	% OF REDUCTION
C	20.47	–
100 FA	7.62	62.77
100 G	7.62	62.77
80F20G	7.62	62.77
80F15G5NS	7.70	62.38
95F5NS	7.69	62.43

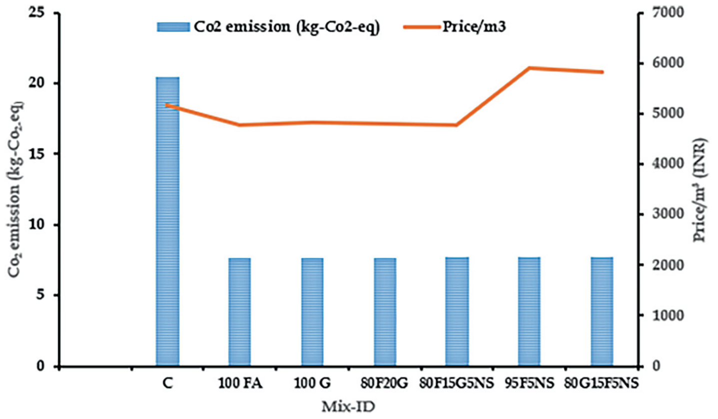

Figure 7: Co$_2$ Emission and cost of materials for different mixtures.

is not much more change in strength as well as chemical composition between ambient and heat curing process, suggesting that heat curing process could be avoided, which may lead to the energy conservation.

Figure 7 shows the carbon di-oxide emission as well as raw material cost of concrete per m^3. It is important to noted that the cost of the newly designed geopolymer concrete is around 7 to 8% cheaper than conventional concrete except nano silica included samples. The price reduction may be because of the 70% cheaper cost of fly ash as well as GGBS than conventional OPC. Meanwhile, the cost of NaOH is high, so the cost reduction comes around 7 to 8%. However, the nano silica inclusion increases the manufacturing cost of concrete, because of the high price of nano silica.

5. CONCLUSION

This experimental study utilized the novel technique to manufacture the geo-polymer concrete using NaOH (12M) as a single activator under ambient curing condition. The aim is to attain the optimum material combination with good mechanical performance as well as reduced carbon emission. The following findings are drawn based on this experimental inquiry.

- In the fresh stage, geopolymer concrete has worse workability than conventional concrete and stiffer mixtures than control concrete, likely due to the high viscosity of the paste.
- Under ambient curing conditions, 100% GGBS with single activator (NaOH)-based Geo-polymer concrete demonstrated superior strength compared to other mixtures. Fly ash and Nano silica additions led to the formation of C-A-H-S and alumino silicates.
- Results from the scanning electron microscope indicate that samples with 100% GGBS under ambient curing conditions have a denser structure without cracks. Nano silica and fly ash enhance geo-polymerization.
- The 80G15F5NS sample exhibits higher levels of calcium alumino silicate hydrate and silicate compared to other GPC samples. However, XRD analysis of ambient and heat-cured samples utilising GGBS as the source material indicates no significant difference.

- The sustainability analysis revealed that all geopolymer concrete combinations utilised in this study reduced carbon emissions by over 60% relative to control concrete.
- Research indicates that geopolymer concrete cured under ambient circumstances with GGBS as the source material and 12 M NaOH as the alkali activator is appropriate for structural applications. Additionally, it offers a greener sustainable construction option.

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